NASA TECHNICAL NOTE

NASA TN D-7390

NASA TN D-7390

EXPERIMENTS TO STUDY STRAIN-GAGE LOAD CALIBRATIONS ON A WING STRUCTURE AT ELEVATED TEMPERATURES

by Richard C. Monaghan and Roger A. Fields

Flight Research Center

Edwards, Calif. 93523

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1973

1. Report No. NASA TN D-7390	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EXPERIMENTS TO STUDY STRAIN-GAGE LOAD CALIBRATIONS ON A WING STRUCTURE AT ELEVATED TEMPERATURES		5. Report Date August 1973
		6. Performing Organization Code
7. Author(s) Richard C. Monaghan and Roger A. Fields		8. Performing Organization Report No. H-763
9. Performing Organization Name and Address NASA Flight Research Center P.O. Box 273 Edwards, California 93523		10. Work Unit No. 501-22-08-00
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Laboratory experiments were performed to study changes in strain-gage bridge load calibrations on a wing structure heated to temperatures of 366° K, 478° K, and 589° K (200° F, 400° F, and 600° F). Data were also obtained to define the experimental repeatability of strain-gage bridge outputs; additionally, experiments were conducted to establish the validity of the superposition of bridge outputs due to thermal and mechanical loads during a heating simulation of Mach 3 flight.

The strain-gage bridge outputs due to load cycles at each of the above temperature levels were very repeatable. A number of bridge calibrations were found to change significantly as a function of temperature.

The sum of strain-gage bridge outputs due to individually applied thermal and mechanical loads compared well with that due to combined or superimposed loads. The validity of superposition was, therefore, established.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
High-temperature strain gage Strain gages Strain-gage calibration	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	25	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

EXPERIMENTS TO STUDY STRAIN-GAGE LOAD CALIBRATIONS ON A WING STRUCTURE AT ELEVATED TEMPERATURES

Richard C. Monaghan and Roger A. Fields
Flight Research Center

INTRODUCTION

The measurement of flight loads on aircraft structures is a common requirement, particularly on experimental and prototype aircraft and vehicles employing new designs. A conventional method of measuring these loads is to make strain measurements on an aircraft structure with strain gages. This method requires the strain gages to be calibrated and load equations to be developed by a procedure such as that discussed in reference 1.

The aerodynamic heating of aircraft structures at high speeds creates problems when flight loads are measured with standard strain-gage techniques. These problems are caused primarily by temperature-induced structural thermal stresses and various strain-gage outputs due to temperature (e. g., apparent strain). Various techniques or procedures have been used for a number of years to extend the use of strain gages to high-temperature applications. For example, temperature-compensated strain gages, special configurations, and the wiring of several strain gages into Wheatstone bridges have been used to reduce temperature effects. Also, limited corrections can be made for changes in gage factor and modulus of elasticity due to temperature, and for laboratory-established apparent strain curves.

These techniques and corrections are still not sufficient, because the strain-gage bridge responses due to structural heating can be large enough to nullify load measurements (ref. 2). A method of determining the thermal responses of strain-gage bridges was investigated and presented in references 2 to 4. This method provides the data necessary to yield useful load measurements by duplicating the flight heating conditions on a flight vehicle or component. The data can be used to select the strain-gage bridges which are the least affected by the thermal environment or to apply corrections to the bridge outputs for the heating, or both.

In references 2 and 3 the heating profile measured on a horizontal stabilizer of the X-15 research airplane during a flight that reached Mach 4.63 was simulated in the laboratory. Heat was applied to the specimen by radiant heating lamps mounted on stainless steel reflectors of the same shape and contour as the stabilizer. It was recognized that there is a basic difference in the type of heating provided by radiant lamps and aerodynamic heating, and that there are other practical limitations that make a perfect temperature simulation impossible. However, it was concluded in reference 2 that this type of heating (radiant) can be made sufficiently accurate to provide an effective method for isolating the effects of heat on strain-gage measurements.

In reference 4 the aerodynamic heating calculated for a Mach 3 cruise flight profile was simulated with radiant lamps in the laboratory on a multispar X-15 wing. Those experiments verified previous results (refs. 2 and 3) and showed that thermal calibrations can be used to select strain-gage bridges and load equations for which temperature effects are minimum or negligible.

The use of the thermal calibration technique remains dependent upon the validity of the strain-gage load calibration and that of the superposition of strain-gage data resulting from flight loads (aerodynamic, inertial, and so forth) and thermal effects. Subsequently, the experiments described in this report were designed and conducted to study the changes, if any, in strain-gage calibrations on a wing structure at various elevated temperatures. This report presents results from these experiments. The elevated temperature calibrations are compared with a calibration performed at room temperature. Results from experiments to determine the repeatability of strain-gage data due to load calibrations are also presented. Additionally, results are presented of experiments to establish how well strain-gage bridge data from the summation of thermal and mechanical loads agree with the laboratory superposition of the same.

These experiments were performed in the NASA Flight Research Center High Temperature Loads Calibration Laboratory at Edwards, Calif. (ref. 5).

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken and the calculations were made in U.S. Customary Units. Factors relating the two systems are presented in reference 6.

TEST SETUP

Test Article

The structure tested was an X-15 wing, which is a short, thin, tapered, low-aspect-ratio, multispar structure. As shown in figure 1, this wing has three main ribs, namely, a root rib, a midspan rib, and a tip rib. The spars between the root and midspan ribs contain corrugated webs. The wing structure in front of the front spar and in back of the rear spar is of the conventional rib type of construction; the leading-edge ribs, however, have corrugated webs. The nose section of the leading edge is a segmented slug or heat sink with a constant radius. The wing-to-fuselage attachment consists of five A-frame assemblies which are an integral part of the wing.

The wing skins, tip rib, front spar, and all of the structure forward of the front spar was made of Inconel X; the remainder of the wing structure material was titanium alloy A-110.

Support Structure

The wing was supported during these experiments by its normal wing-to-fuselage A-frame attachment points, as shown in figure 2. The 10 attachment points were pinned to cantilevered support arms which in turn were fixed to a rigid structure. The support arms were designed with moderate stiffness to allow thermal deformation of the wing to take place without overstressing the wing attachment points. No attempt was made to simulate the wing attachment provided by the airplane.

Instrumentation

Strain gages were located at the wing root and A-frames as shown in figure 3. The gages were installed and wired to form shear, bending, and tension bridges; the different bridge configurations are illustrated in figure 4. The strain gages that form bending bridges at the wing root are of the weldable type; the remainder are of the bonded-foil type. All the gages at the root were installed many years before the experiments discussed in this report, and only those that were still operable were used in the experiments. Several more became inoperable during the course of the tests.

The wing was also instrumented with 89 thermocouples. The location of these thermocouples is described in reference 4.

Each of the 10 support arms (see fig. 2) was instrumented with strain-gage bridges to measure axial load and bending moment about both the horizontal and the vertical axes.

The thermocouple and strain-gage bridge test data were recorded on the 1200-channel digital data-acquisition system of the High Temperature Loads Calibration Laboratory. The system has measurement ranges as sensitive as ±5 millivolts full scale with a resolution of 2.5 microvolts.

Loading and Heating Equipment

A major problem in applying mechanical loads during a heating simulation is making an attachment to a structure without adding a heat sink which creates thermal stresses that are unwanted or damaging, or both. It is also necessary to design the loading mechanism so that it causes a minimum of interference to the heating system. In the experiments reported herein a substantial load was applied directly to the test structure through a 1.90-centimeter- (0.75-inch-) wide, 0.10-centimeter- (0.040-inch-) thick, 4130 steel corrugated strip at the midspan rib location (fig. 5). This attachment caused a minimum heat sink in contact with the surface of the test structure. Certain rivets were removed from the wing, and the corrugated strip was fastened with blind rivets through the resulting holes. Cables were attached to the tops of the corrugations and passed through the reflector with a minimum of alteration to the heating system. The cables were thermally insulated to prevent them from becoming overheated as they passed between the heat lamps. No detrimental effects were observed in the flight heating profile on any part of the structure due to the loading system attachment.

Figure 6 shows the three hydraulic actuators, their load cells, and the whippletree arrangement used to apply equal loads to each of the test panel attachment cables. Each actuator was controlled by a closed-loop system that used load measurements indicated by a load cell as feedback. All three actuators were operated by a single programed loading time history.

The heating system is identical to that used in previous experiments and reported on in detail in reference 4. Briefly, infrared heating lamps were mounted on polished stainless steel reflectors of the same shape and contour as the wing. Lamp location and density were designed to simulate flight heating conditions over the wing. The heat lamps were divided among 50 individually controlled zones (24 on the upper surface, 24 on the lower surface, and two on the leading edge). Each zone was controlled independently by a closed-loop system that used the temperature indicated by a thermocouple in that zone as feedback. The temperature in each zone was maintained by the lamps according to a preprogramed temperature time history.

TEST PROCEDURE

Two series of experiments were conducted: The first series was designed to investigate the strain-gage bridge responses that resulted from identical load conditions at several equilibrium temperatures. The second was designed to establish how well the superposition of strain-gage bridge data from independently applied thermal and mechanical loadings on the wing agreed with data for the combined loads.

In the first series of experiments the wing was heated to uniform surface temperatures of 366° K, 478° K, and 589° K (200° F, 400° F, and 600° F) and it was held at each of these temperature levels long enough to allow the internal structural temperatures to reach equilibrium. Loads were applied to the wing at room temperature and at the equilibrium temperature levels indicated above. Load was applied in 10-percent increments to a maximum of 32,000 newtons (7,200 pounds). The total load represented approximately 50 percent of the design shear and bending load at the wing root.

This heating and loading procedure was repeated two additional times to establish the repeatability of strain-gage bridge data inclusive of all sources of error.

The second series of experiments had two parts: The first consisted of heating and loading the wing simultaneously. A load of 32,000 newtons (7,200 pounds) was applied with hydraulic actuators to the wing loading attachment and maintained while the heating of a Mach 3 cruise flight profile was simulated on the wing. This heating profile was calculated for each of the 50 independently controlled zones or areas on the wing. A typical wing-surface temperature profile is shown in figure 7. The figure shows both the calculated (programed) temperatures and the temperatures measured during laboratory heating. Additional information on the heating calculations and simulation is presented in reference 4.

The second part of this series of experiments consisted of simulating only the heating of Mach 3 cruise flight on the wing. These final experiments made it possible to determine the strain-gage bridge outputs due to mechanical load only, heating only, and combined heating and loading.

RESULTS AND DISCUSSION

Thermal Effects on Calibration

Figures 8(a) and 8(b) present typical data for the repeatability of the outputs of two strain-gage bridges due to loads on the wing at room temperature and at a uniform skin temperature of 589° K (600° F). The 589° K (600° F) data in these figures were not corrected for differences (zero shifts) in bridge outputs at zero load. Zero shift is due to several factors, including strain-gage creep or drift and temperature deviations between experiments. With the zero shift corrected, it was determined that the data were repeatable to better than 0.05 of the nondimensional strain-gage bridge output (μ). A nondimensional strain-gage bridge output of 0.05 is equal to approximately 3 percent of the mean value of all the strain-gage bridge outputs for the 32,000-newton (7,200-pound) load conditions.

The strain-gage bridge outputs were plotted as a function of load for each bridge and for each equilibrium temperature level (including room temperature). All data were corrected for zero shift. Variations of less than $\pm 0.05\mu$ between bridge outputs at different temperatures were considered to be within the accuracy of the data; all other variations were considered to be changes in the bridge sensitivity to load (calibration). The slopes of the bridge outputs as a function of load are listed in table 1.

As can be seen in the table, only bridges located on the wing A-frame structure (numbers 4 to 9, 11 to 13, 16, 19, 21, and 22) had changes in slope. Those slopes consistently either increased or decreased with temperature increases; however, the changes are not necessarily linear. To explain these slope changes, let us first consider the maximum temperatures to which the various bridges were subjected during the 589° K (600° F) heating test. The bridges at the wing root (numbers 25 to 35) were heated to 589° K (600° F), and those on the A-frames (numbers 1 to 24) were heated to a range from approximately 367° K to 422° K (200° F to 300° F). In other words, the bridges that were heated to the highest temperatures did not have slope changes. Therefore, the magnitude of temperatures at the bridge locations is not the predominant factor in this case.

Two significant changes in bridge sensitivity to load at elevated temperature are (1) decreasing strain-gage gage factor and (2) decreasing modulus of elasticity of the structure. The first of these has the effect of reducing bridge responses at elevated temperature, and the latter increases bridge responses because of higher structural strains due to load. These effects cancel each other to a certain extent, depending upon the type of material and strain gage.

Figure 9 shows the percentage of change in bridge output due to the above effects that can be expected for the tests of this report. Curves are shown for the changes in output due to gage factor and to modulus variations of Inconel X and titanium alloy A-110.[1]

[1]Strain-gage factor information was supplied by the gage manufacturer; material modulus of elasticity information was supplied by the wing manufacturer.

The root strain gages are installed on the Inconel X material. The net change in gage sensitivity of these gages would be approximately 2 percent at 589° K (600° F); this change is obscured in the inaccuracy of the test data.

The A-frame gages were installed on titanium alloy A-110. The A-frame area was heated from the skin side while the opposite side was exposed to room-temperature air. The resulting temperature distribution for a typical A-frame section is approximately as shown in figure 10. Since these temperatures vary considerably, it is not certain what the sensitivity change of the bridges due to modulus variation would be. A combined change (modulus plus gage factor) of 12 percent would be expected if the A-frame were uniformly heated to 589° K (600° F); however, a change of approximately 7 percent would more probably correspond to the average temperature of the cross section. Although this should be a measurable effect, it is not sufficient to explain the magnitude of the slope changes of the A-frame bridges.

Upon further investigation, it was found that the load sensitivities of the support arm strain-gage bridges changed noticeably during the various tests, as shown in figure 11. Since these bridges were remote from the heating, it is believed that the reason for these changes and the primary reason for the changes in the response of the A-frame gages are geometry changes due to thermal deformation. Thermal gradients such as those shown in figure 10 cause structural deflections that change the local strain distribution and the overall load paths.

It can be deduced from the preceding discussion that a change in strain-gage calibration due to elevated temperatures on a particular structure is dependent upon (1) the temperature characteristics of the strain gage, (2) the material upon which the gage is installed, and (3) variations in load paths or structural component load sensitivity resulting from the thermal deformation of a structure. Strain-gage bridge locations that are obviously susceptible to thermally induced structural geometry changes, such as the wing A-frames, should be avoided. Also, in cases where heating might cause changes in strain-gage calibration, a high-temperature check calibration may be necessary. Although not considered a factor in these experiments, it should not be overlooked that a nonuniform surface temperature distribution could produce varying modulus of elasticity changes and result in different structural stiffnesses at elevated temperatures.

Superposition of Thermal and Mechanical Loads

Figure 12 presents typical data from the experiments that were conducted to study the superposition of thermal and mechanical loads. The figure shows strain-gage bridge outputs due to loading only, heating only, the sum of the foregoing, and the laboratory superposition of loading and heating. The differences between the sum and the superposition data for bridges that exhibited load calibration slope changes at elevated temperatures (see table 1) are consistent with those changes. In other words, a bridge that had less output due to the laboratory superposition than due to the sum of the individual components also had a calibration slope which decreased at elevated temperature; conversely, a bridge which had greater output due to laboratory superposition than due to the sum of individual components also had a calibration slope which increased at elevated temperature. Corrections were applied to the laboratory superposition data (circular symbols) using the data in table 1. The resulting data are shown as the square symbols in figures 12(c), 12(d), and 12(e). In each case, the corrections provided substantial improvements in the comparisons.

The remaining differences between the sum and the corrected superposition data are generally less than $\pm 0.1\mu$. This is about twice as large as the previously established repeatability of the strain-gage bridge data due to load. A reason for the increased difference is the additional error in the repeatability of the heating of a particular flight profile (Mach 3). The nonuniform heating of this profile causes larger thermal strains than the uniform heating of prior experiments and, hence, increases the probability of error. The total error is believed to be acceptable experimental error for combined heating and loading.

The results of these experiments, therefore, show that the superposition of thermally and mechanically applied loads is valid and can be performed satisfactorily.

CONCLUDING REMARKS

Laboratory experiments were conducted on a multispar wing structure to study the effect of structural heating on strain-gage calibrations used for measuring aerodynamic loads. Loads were applied to the wing during uniform heating environments of 366° K, 478° K, and 589° K (200° F, 400° F, and 600° F); each of these temperature conditions was repeated three times. It was found that A-frame and wing-root strain-gage bridges had repeatable outputs due to load at the various temperature levels. However, the load calibrations of approximately one-half of the bridges located on the A-frames changed significantly as a function of temperature. These changes were not necessarily linear with changes in temperature.

It was concluded that changes in strain-gage bridge calibration responses due to elevated temperature for this structure were due primarily to: (1) the temperature characteristics of the strain gages, (2) the temperature-degraded elastic modulus of the material to which the strain gage was attached, and (3) load path variations due to thermal deformations of the A-frame structure. Other effects such as varying modulus of elasticity due to nonuniform temperature distribution can affect the structural characteristics at elevated temperatures and should not be overlooked.

Experiments were also conducted to study the superposition of strain-gage bridge outputs due to thermal and mechanical loadings on the wing structure. Bridge outputs due to independently applied thermal and mechanical loads were summed and compared to outputs obtained by the combined applications of those loads. Outputs from the two cases agreed closely except for bridges that had calibration changes at elevated temperatures during the foregoing experiments. After corrections were made for the calibration changes, the output comparisons of those bridges also agreed closely. It was concluded that the superposition of strain-gage bridge outputs due to heating and loading is valid when appropriate corrections are made for temperature-induced calibration changes. The latter may require the use of elevated temperature load calibrations.

As an additional development of these investigations, a successful method of applying structural load during a high-temperature simulation was established. The loading system applied substantial loads directly to the structure without any detrimental effects on the designed flight heating profile over any part of the structure.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., March 12, 1973

REFERENCES

1. Skopinski, T. H.; Aiken, William S., Jr.; and Huston, Wilber B.: Calibration of Strain-Gage Installations in Aircraft Structures for the Measurement of Flight Loads. NACA Rept. 1178, 1954.

2. Fields, Roger A.: A Study of the Accuracy of a Flight-Heating Simulation and Its Effect on Load Measurement. NASA TN D-5741, 1970.

3. Fields, Roger A.; and Vano, Andrew: Evaluation of an Infrared Heating Simulation of a Mach 4.63 Flight on an X-15 Horizontal Stabilizer. NASA TN D-5403, 1969.

4. Fields, Roger A.; Olinger, Frank V.; and Monaghan, Richard C.: Experimental Investigation of Mach 3 Cruise Heating Simulations on a Representative Wing Structure for Flight-Loads Measurement. NASA TN D-6749, 1972.

5. Sefic, Walter J.; and Anderson, Karl F.: NASA High Temperature Loads Calibration Laboratory. NASA TM X-1868, 1969.

6. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors (Revised). NASA SP-7012, 1969.

TABLE 1.–CHANGES IN STRAIN-GAGE BRIDGE OUTPUT PER LOAD AT FOUR EQUILIBRIUM TEMPERATURES

(a) SI Units

Strain-gage bridge number	Slope, μ/newton			
	Room temperature	366° K	478° K	589° K
A-frame gages				
1	-6.81×10^{-5}	-6.81×10^{-5}	-6.81×10^{-5}	-6.81×10^{-5}
2	-10.42	-10.42	-10.42	-10.42
3	-4.56	-4.56	-4.56	-4.56
4	-8.25	-8.00	-7.81	-7.33
5	-4.28	-4.44	-4.69	-5.11
6	6.58	6.58	7.08	7.25
7	9.00	8.56	7.81	7.31
8	-7.50	-6.97	-6.50	-5.94
9	5.50	4.89	4.61	4.42
10	No calibration	------------	------------	------------
11	4.00	3.56	3.33	3.22
12	-2.81	-3.19	-3.44	-3.28
13	5.40	5.30	5.25	4.75
14	1.00	1.00	1.00	1.00
15	No calibration	------------	------------	------------
16	-8.15	-7.53	-7.34	------------
17	1.97	1.97	1.97	1.97
18	-3.05	-3.05	-3.05	-3.05
19	4.50	5.40	5.75	6.10
20	.42	.42	.42	.42
21	-3.75	-3.92	-4.28	-4.61
22	5.94	6.17	6.67	7.33
23	No calibration	------------	------------	------------
24	No calibration	------------	------------	------------
Wing-root gages				
25	-2.75	-2.75	-2.75	-2.75
26	-3.47	-3.47	-3.47	-3.47
27	No calibration	------------	------------	------------
28	-4.00	-4.00	-4.00	-4.00
29	No calibration	------------	------------	------------
30	-4.67	-4.67	-4.67	-4.67
31	No calibration	------------	------------	------------
32	-4.56	-4.56	-4.56	-4.56
33	-3.39	-3.39	-3.39	-3.39
34	-2.56	-2.56	-2.56	-2.56
35	-2.56	-2.56	-2.56	-2.56

TABLE 1.– CHANGES IN STRAIN-GAGE BRIDGE OUTPUT PER LOAD AT FOUR EQUILIBRIUM TEMPERATURES - Concluded

(b) U.S. Customary Units

Strain-gage bridge number	Slope, μ/pound			
	Room temperature	200° F	400° F	600° F
A-frame gages				
1	-3.03×10^{-4}	-3.03×10^{-4}	-3.03×10^{-4}	-3.03×10^{-4}
2	-4.63	-4.63	-4.63	-4.63
3	-2.03	-2.03	-2.03	-2.03
4	-3.67	-3.56	-3.47	-3.26
5	-1.90	-1.97	-2.09	-2.27
6	2.93	2.93	3.15	3.22
7	4.00	3.81	3.47	3.25
8	-3.34	-3.10	-2.89	-2.64
9	2.45	2.18	2.05	1.97
10	No calibration	-----------	-----------	-----------
11	1.78	1.58	1.48	1.43
12	-1.25	-1.42	-1.53	-1.46
13	2.40	2.36	2.34	2.11
14	.44	.44	.44	.44
15	No calibration	-----------	-----------	-----------
16	-3.63	-3.35	-3.26	-----------
17	.88	.88	.88	.88
18	-1.36	-1.36	-1.36	-1.36
19	2.00	2.40	2.56	2.71
20	.19	.19	.19	.19
21	-1.67	-1.74	-1.90	-2.05
22	2.64	2.74	2.97	3.26
23	No calibration	-----------	-----------	-----------
24	No calibration	-----------	-----------	-----------
Wing-root gages				
25	-1.22	-1.22	-1.22	-1.22
26	-1.54	-1.54	-1.54	-1.54
27	No calibration	-----------	-----------	-----------
28	-1.78	-1.78	-1.78	-1.78
29	No calibration	-----------	-----------	-----------
30	-2.08	-2.08	-2.08	-2.08
31	No calibration	-----------	-----------	-----------
32	-2.03	-2.03	-2.03	-2.03
33	-1.51	-1.51	-1.51	-1.51
34	-1.14	-1.14	-1.14	-1.14
35	-1.14	-1.14	-1.14	-1.14

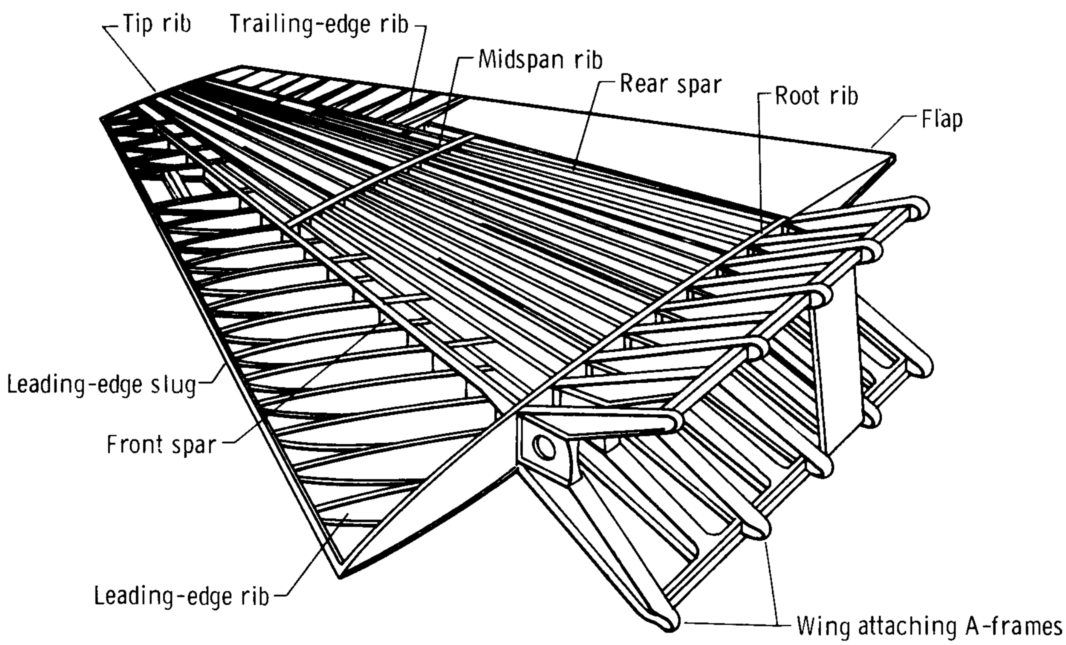


Figure 1. X-15 wing structure.

E-19679

Figure 2. Test wing and support structure.

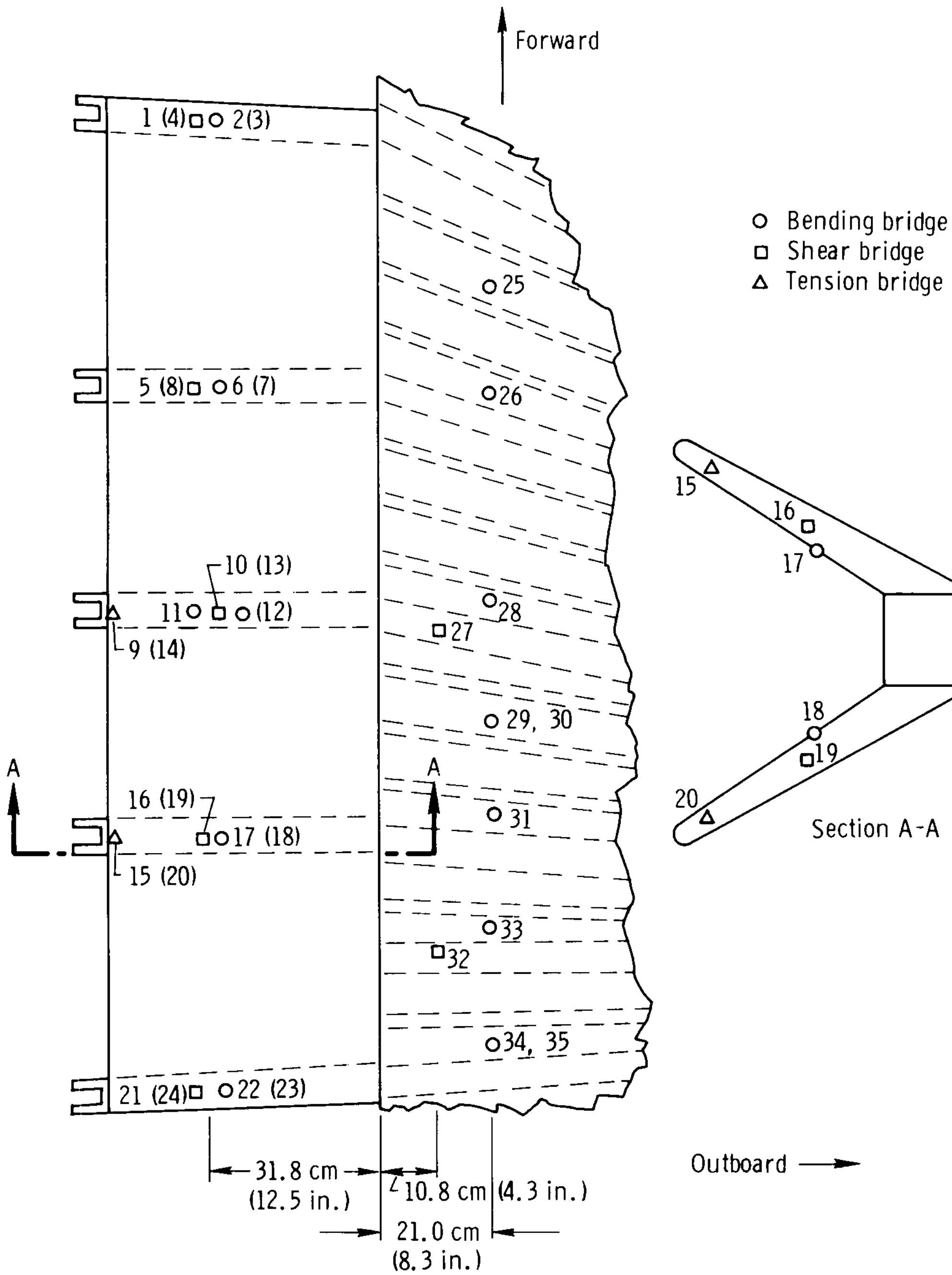
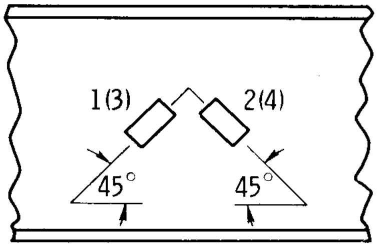
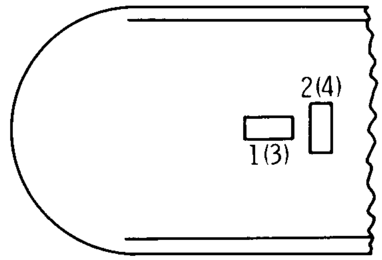


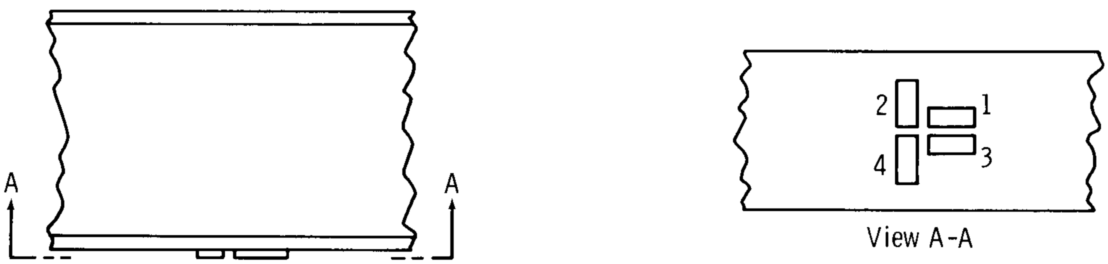
Figure 3. Strain-gage bridge number and location. Numbers in parentheses indicate bridges on the lower A-frame leg.



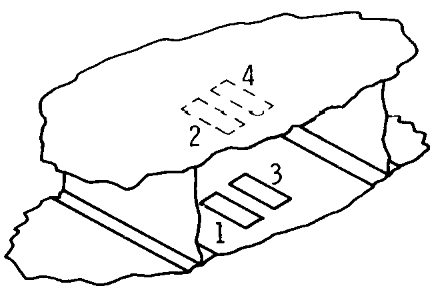
(a) Shear (A-frame and root).



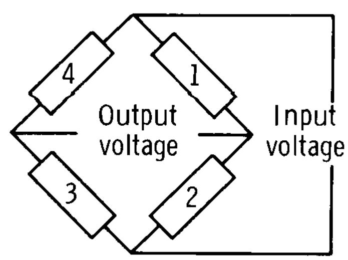
(b) Tension (A-frame).



(c) Bending (A-frame).



(d) Bending (root).



(e) Wheatstone bridge.

Figure 4. Strain-gage bridge configurations. Numbers indicate strain-gage numbers with reference to the bridge wiring shown in sketch (e). Numbers in parentheses indicate gages on the opposite side of the member.

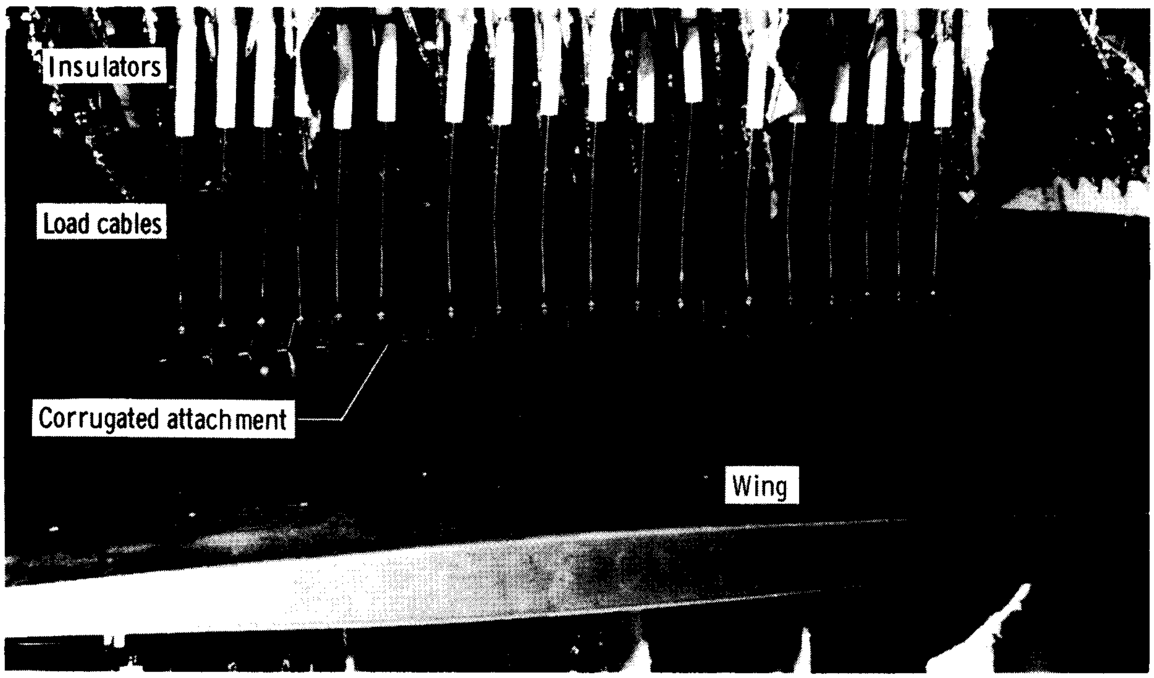


Figure 5. Wing loading attachment. E-21081

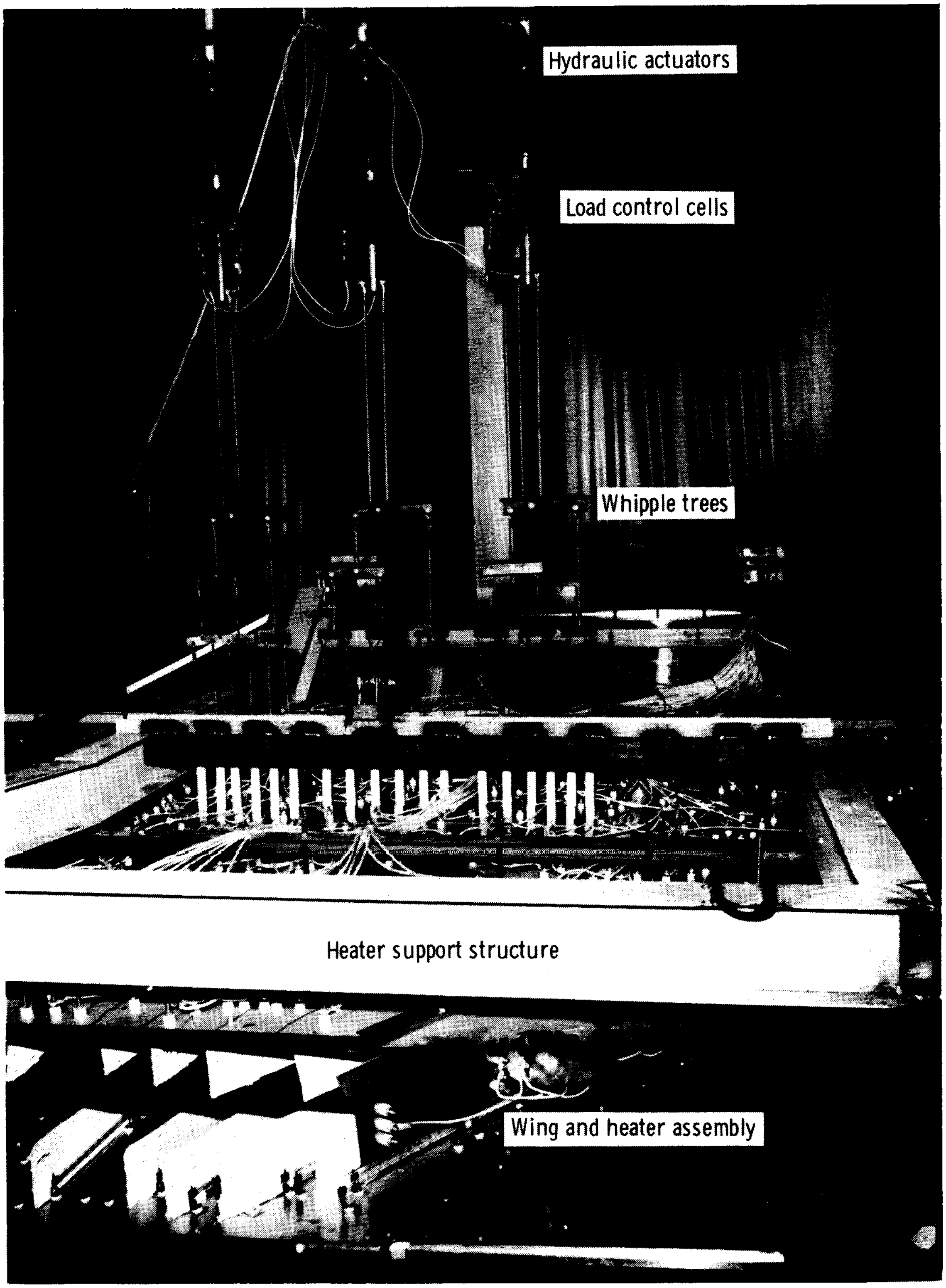


Figure 6. Test setup for combined heating and loading experiments on the X-15 wing. E-21080

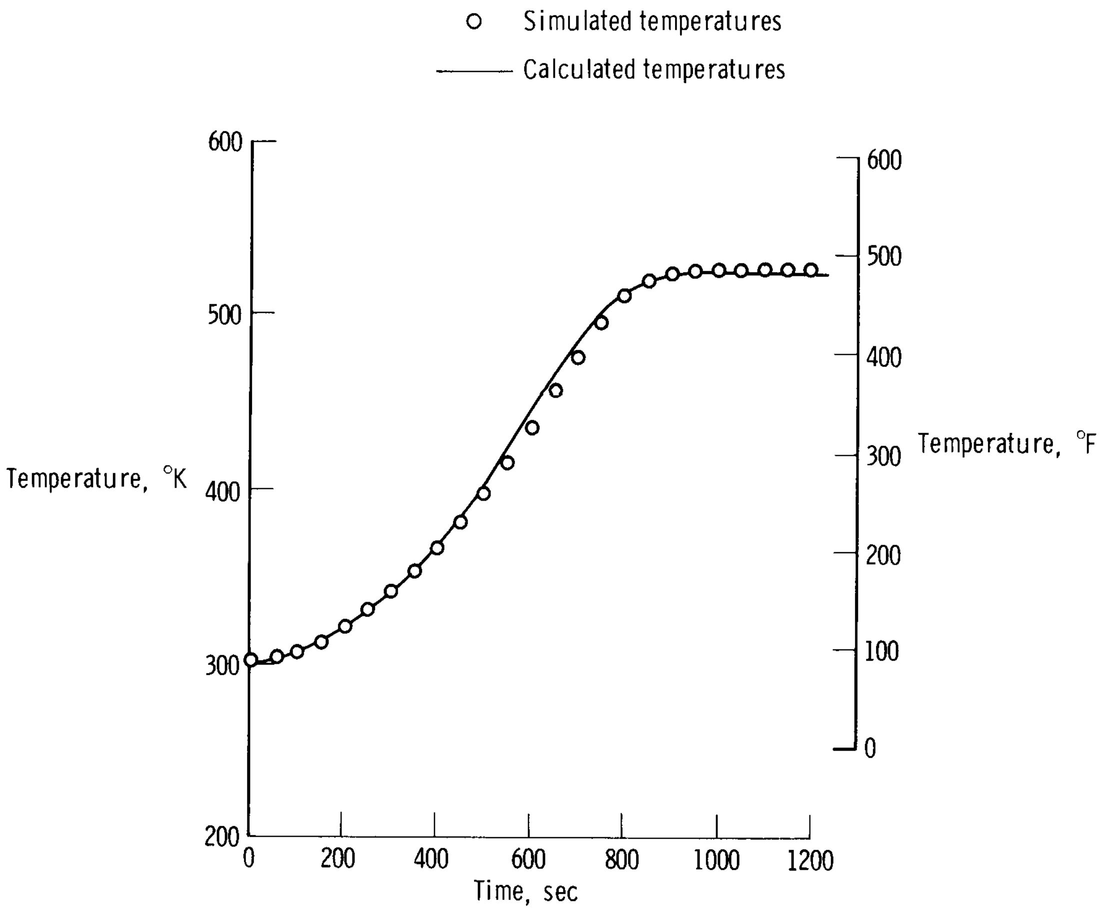
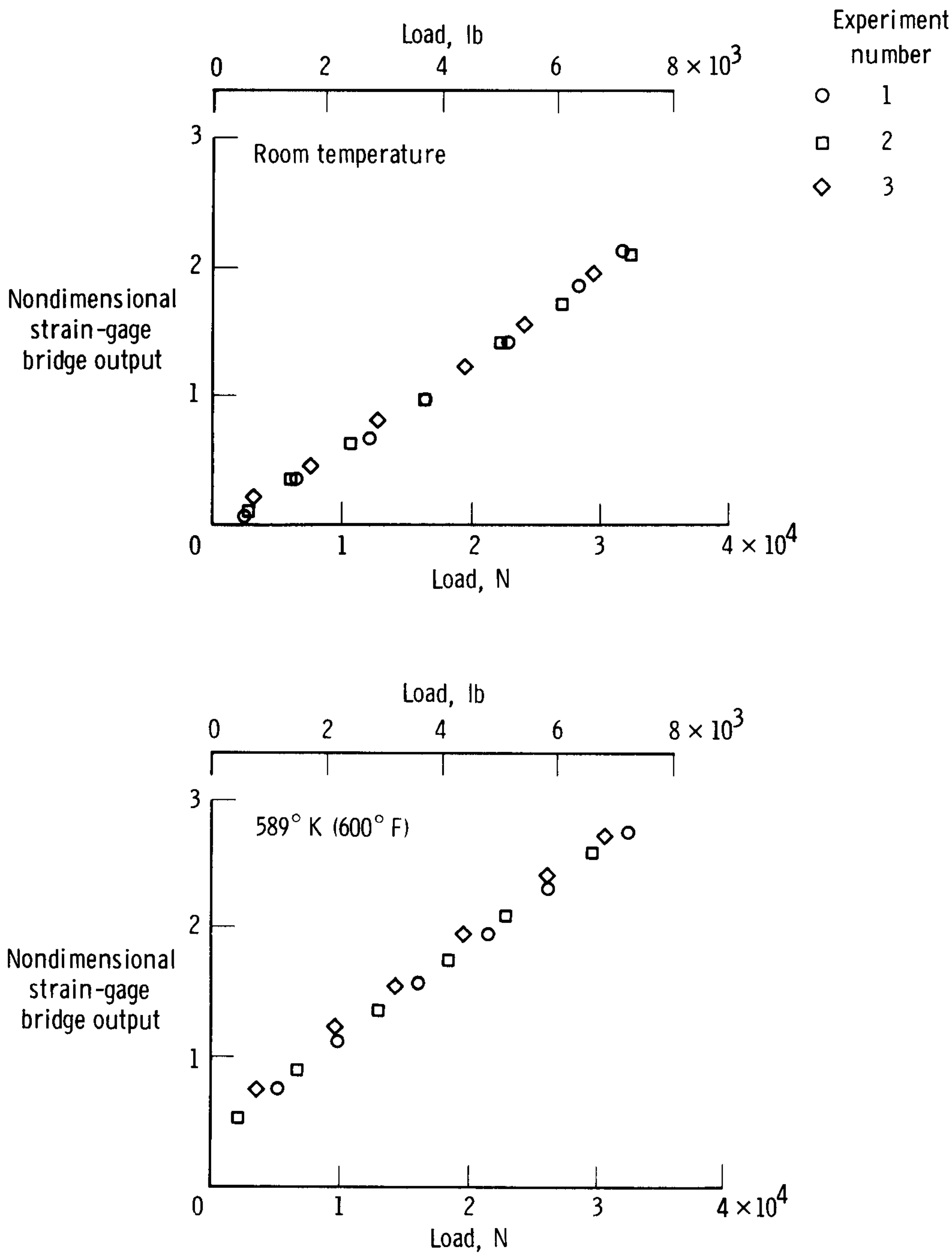
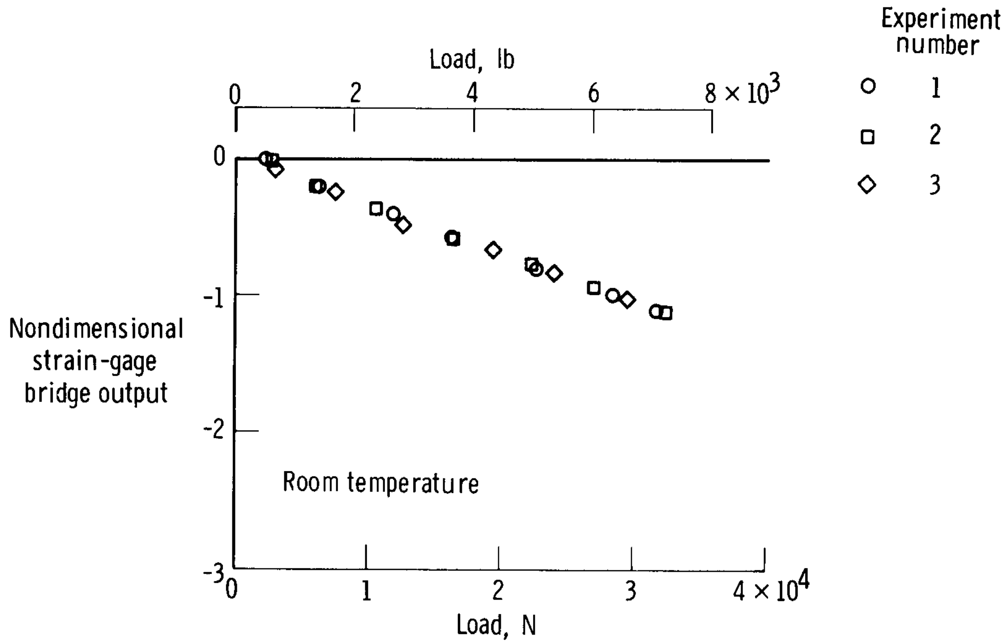


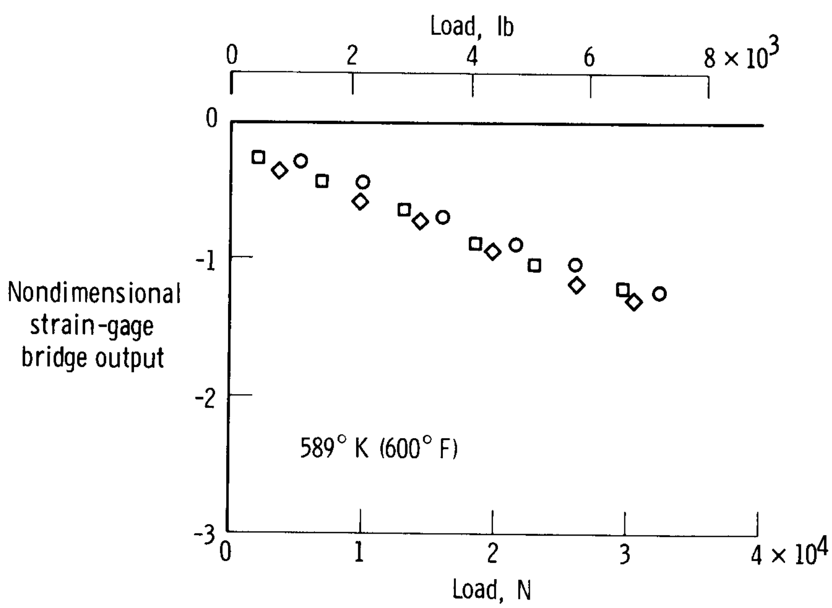
Figure 7. Typical heating profile for the simulation of Mach 3 cruise flight that was used in the superposition experiments.



(a) Strain-gage bridge number 6.

Figure 8. Repeatability of strain-gage bridge output due to load for similar temperature conditions.





(b) Strain-gage bridge number 26.

Figure 8. Concluded.

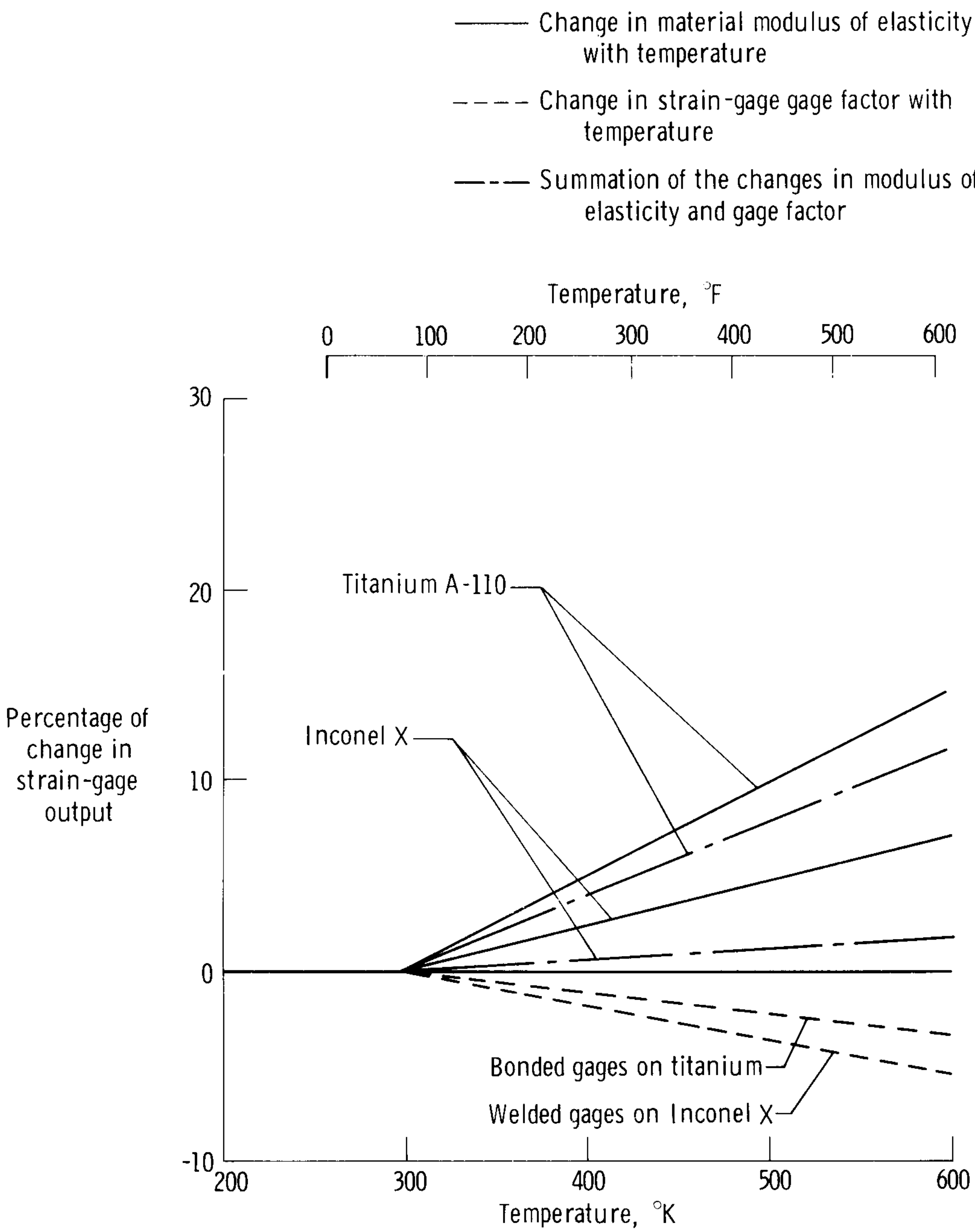


Figure 9. Changes in strain-gage sensitivity to load at elevated temperatures due to changes in modulus of elasticity and gage factor.

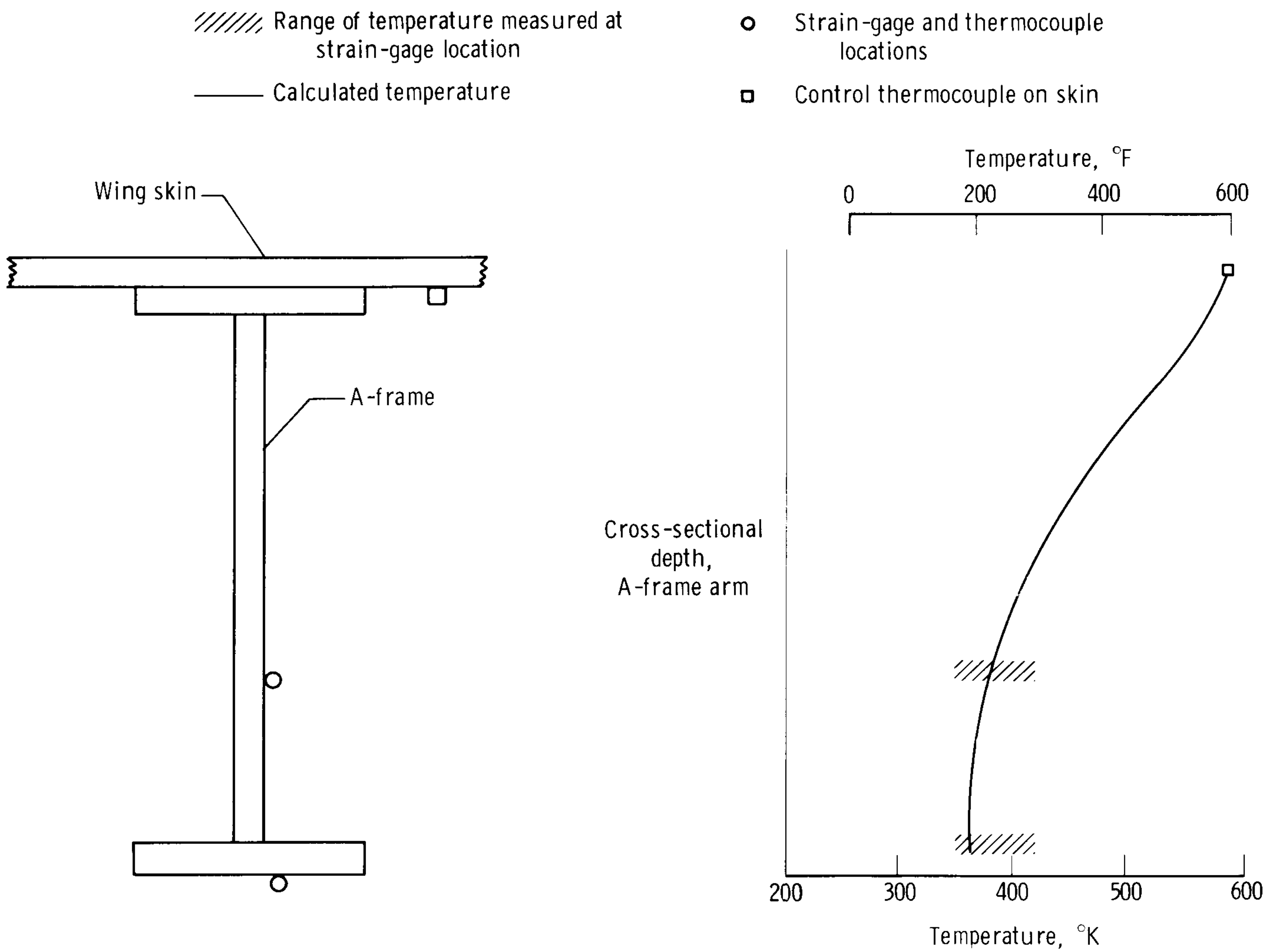


Figure 10. A-frame cross-sectional temperature distribution for the 589° K (600° F) test.

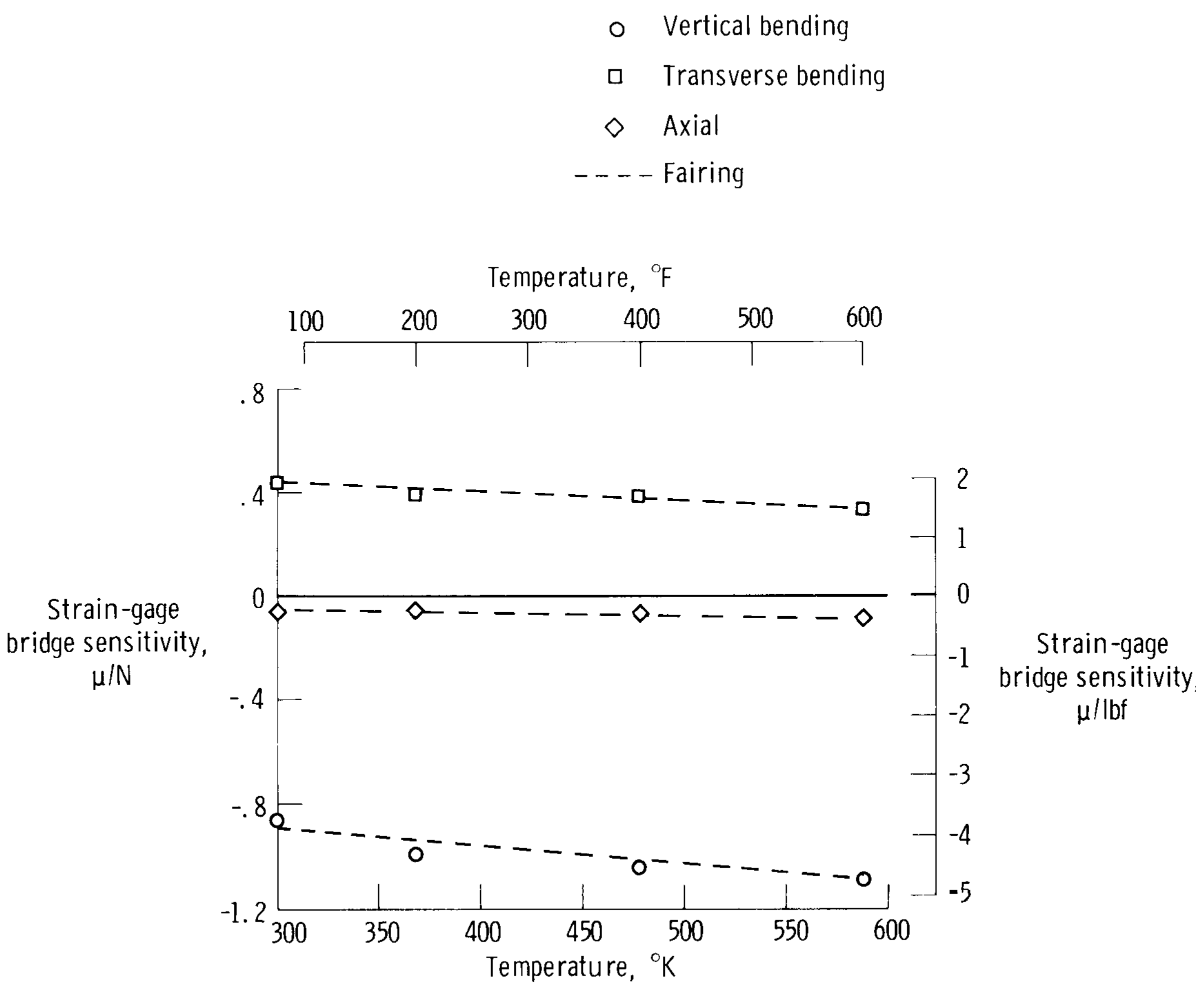
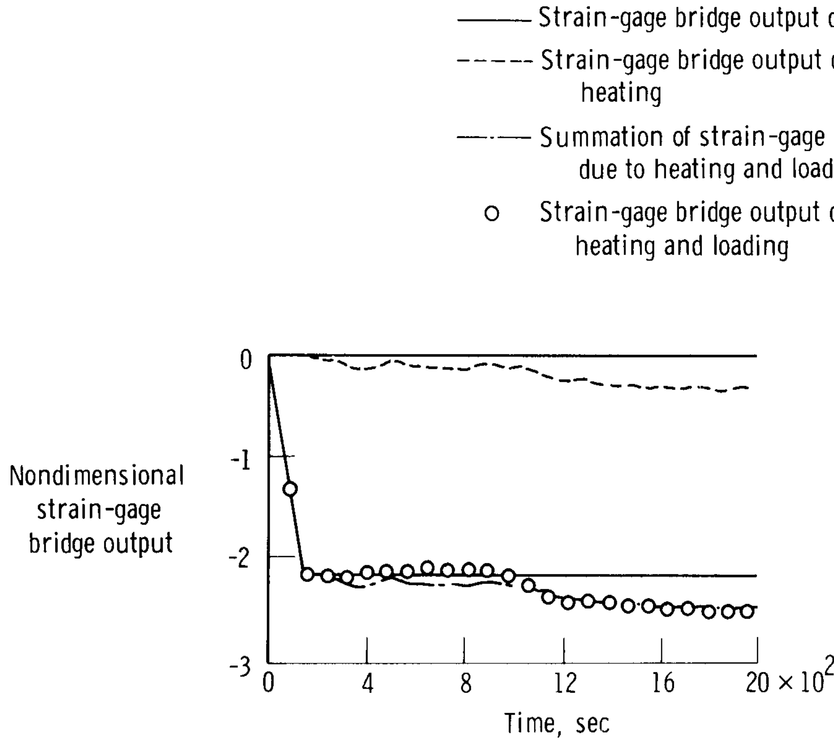
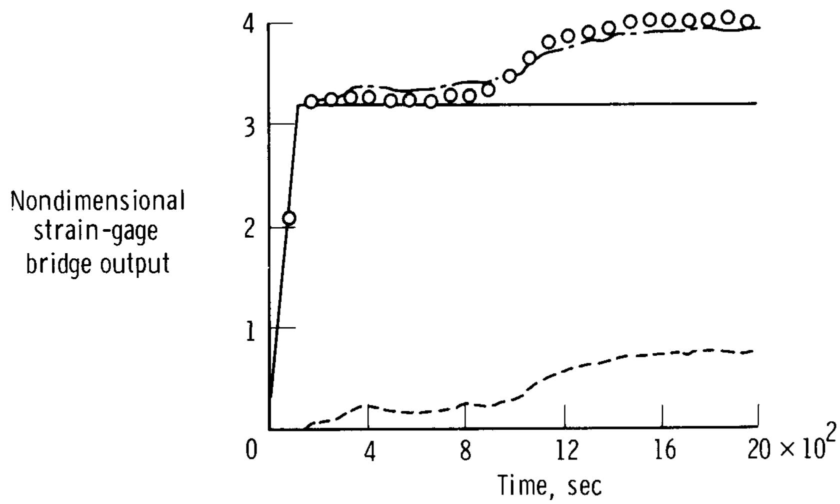


Figure 11. Typical support arm bridge sensitivities to load as a function of control temperature on the wing.

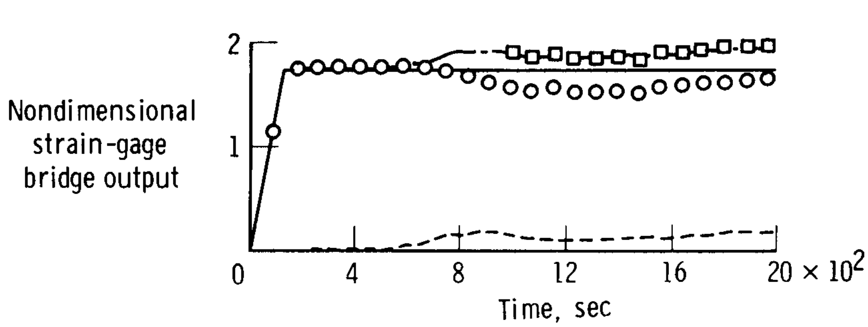


(a) Strain-gage bridge number 1.

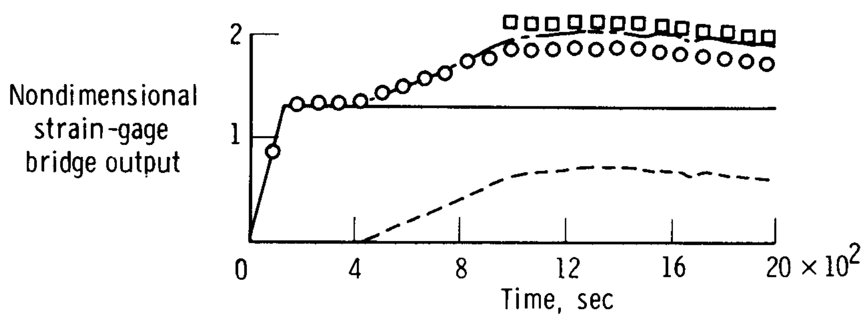


(b) Strain-gage bridge number 2.

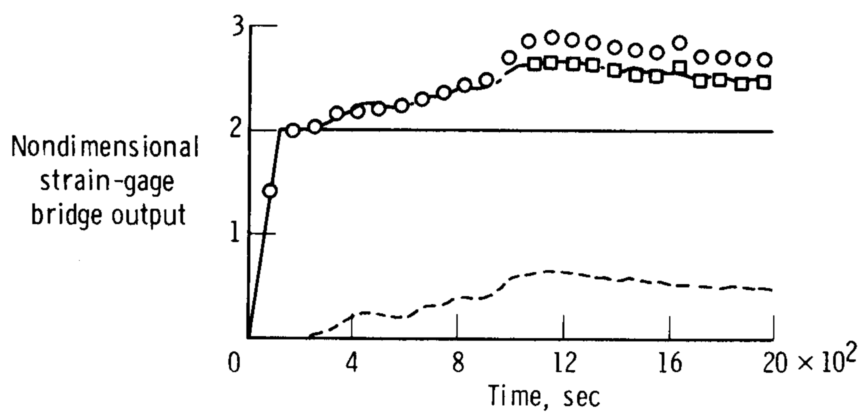
Figure 12. Individual, summed, and superimposed strain-gage bridge outputs due to separate and combined structural loads and Mach 3 heating simulation.



(c) Strain-gage bridge number 9.

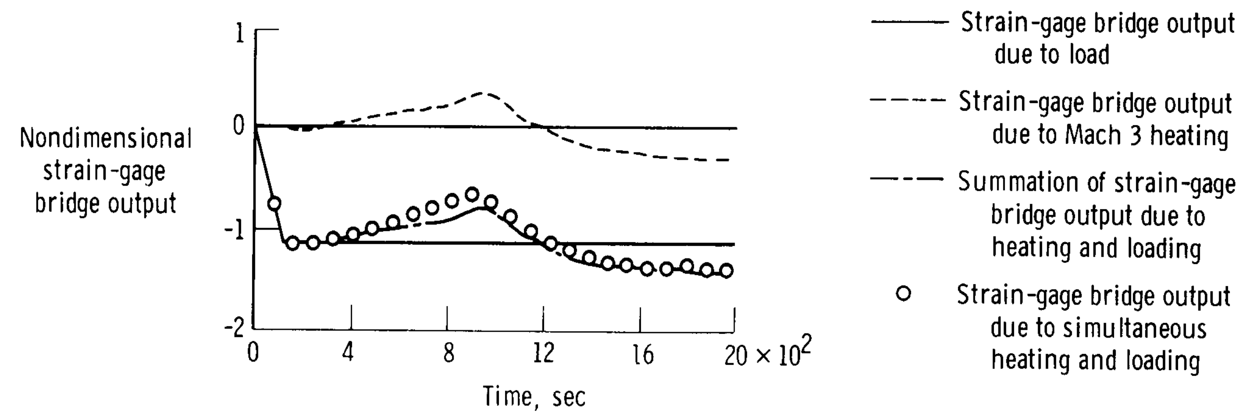


(d) Strain-gage bridge number 11.

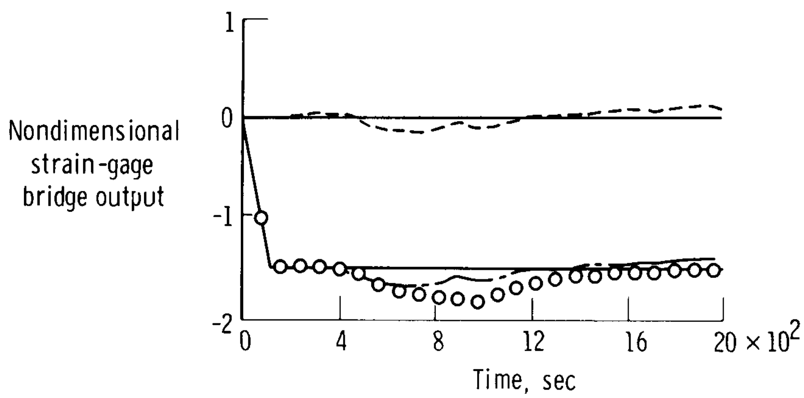


(e) Strain-gage bridge number 22.

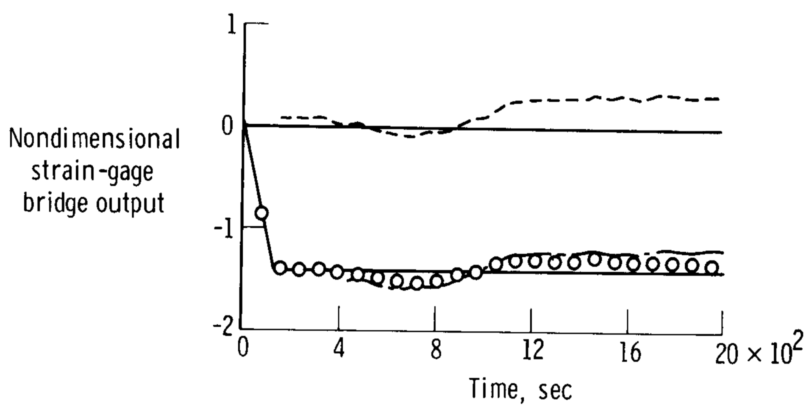
Figure 12. Continued.



(f) Strain-gage bridge number 26.



(g) Strain-gage bridge number 30.



(h) Strain-gage bridge number 31.

Figure 12. Concluded.